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RESEARCH MEMORANDUM

SIMULATOR INVESTIGATION OF COMMAND REACTION CONTROLS

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High-Speed Flight Station
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RESEARCH MEMORANDUM

SIMULATOR INVESTIGATION OF COMMAND REACTION CONTROLS*

By Euclid C. Holleman and Wendell H. Stillwell

SUMMARY

Reaction controls that command velocity and attitude have been investigated and are compared to controls that command acceleration. Proportional acceleration reaction controls were found to be satisfactory over a much wider range of control effectiveness than were the on-off acceleration controls. The velocity and attitude controls were superior to either of the acceleration controls. The proportional acceleration, velocity, and attitude command systems were found to be comparable in fuel required and were insensitive to practical rocket system lags. Dynamic pressure through dihedral effect complicated the control problem, but the velocity and attitude systems minimized these effects. Successful entry could be accomplished with either of the control systems, but with the acceleration command system the task required much more attention from the pilot.

INTRODUCTION

Exploitation of the ballistic capabilities of present or contemplated manned vehicles requires the use of some form of reaction control. Attitude control will then be possible beyond aerodynamic flight limits. Figure 1 shows altitude plotted against Mach number with the shaded area representing dynamic pressure of from 5 to 10 pounds per square foot. It is believed that, generally, above this region reaction controls will be required.

Initial investigations of reaction control usage were made by using an analog simulator. These studies investigated on-off acceleration reaction controls which gave adequate control, but which required constant attention to the control task. Such a reaction control system was designed for the X-1B airplane and has been ground-tested by using a three-degree-of-freedom simulator. Flight tests of these reaction controls have been initiated.

*Title, Unclassified.

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This paper evaluates the effectiveness of reaction controls that command velocity and attitude and compares these systems to the acceleration command systems. Although much of the data were obtained for ideal systems at zero dynamic pressure, some results are also available to assess the effects of low dynamic pressure as well as assumed rocket system lags.

SYMBOLS

K_A	attitude feedback gain
K_V	velocity feedback gain
q	dynamic pressure, lb/sq ft
β	angle of sideslip, deg
δ_θ	pitch control, percent
δ_φ	roll control, percent
δ_ψ	yaw control, percent
θ	pitching angle, deg
$\dot{\theta}$	pitching velocity, deg/sec
φ	angle of bank, deg

METHOD

This study was performed utilizing a closed-loop simulation consisting of an analog computer, oscilloscope for presentation, control stick, and pilot. The analog computer was used to solve the differential equations that represented the airplane and control system. Three degrees of freedom were assumed for the zero dynamic pressure case, and five degrees of freedom for the finite dynamic pressure case. Representative research airplane mass and basic aerodynamic characteristics (table I) for a Mach number of 4.5 were used for the assumed problem. A three-axes control stick (fig. 2), which is similar to the controller being used in the X-1B airplane, was used for control. This stick required up-and-down motion for pitch control, side-to-side motion for yaw control, and rotation for roll control.

Also shown in the figure is the presentation to the pilot. A trace on an oscilloscope moved up and down to represent pitch, rolled to signify roll, and a meter indicated yaw.

Since it was desired to use these control systems for orientation as well as stabilization in the reaction control region, several evaluation tasks were employed. The response and precision of control were evaluated by making pitch, yaw, and roll changes in attitude and by coordinating these changes. This task is referred to as the orientation task. Another control task consisted of attempting to retain initial attitude after the imposition of a sudden constant acceleration of 2 degrees per second^2 in pitch and yaw and is termed the stabilization task.

RESULTS AND DISCUSSION

Previous studies of acceleration on-off reaction controls indicated desirable levels of control effectiveness and proportioning. A summary of these results is presented in figure 3, which shows satisfactory control regions that are functions of roll control effectiveness and control effectiveness ratio. (Control effectiveness is defined as the angular acceleration produced by full control. Control effectiveness ratio is the ratio of roll control effectiveness to yaw or pitch control effectiveness.)

For a stabilizing task the on-off acceleration controls were satisfactory within the triangular region shown. Higher control effectiveness resulted in overcontrol tendencies. Also shown is the value presently being flight tested with the X-1B airplane. The limits of the present study are shown by the bars. Although this study was not as comprehensive in determining the limits of satisfactory control as the previous on-off study was, the three systems - proportional acceleration command, velocity command, and attitude command - gave satisfactory control over the range shown, which is a much larger range of control effectiveness than was obtained with the on-off controls. Somewhat arbitrary values of control effectiveness of 20 degrees per second^2 for roll and a control ratio of 4 were used for all the results presented. The results that follow compare the proportional acceleration, velocity, and attitude systems.

For an auxiliary control system such as the reaction control, economical operation is of great importance. Fuel requirements are one indication of the effectiveness of the closed-loop control. Figure 4 shows a simple block diagram which describes the systems under consideration. Also shown is the effect of system feedback gain for the velocity command and the attitude command system on the relative fuel required for the stabilization task. The fuel requirements have been normalized to the acceleration command system which is represented by zero velocity gain. For the velocity command system the relative fuel required decreases with increasing feedback gain. A gain of 1.5 gave good response as well as reasonably good economy and was used for most of the tests. In the range of attitude feedback gain from 0.1 to 0.5 the relative fuel required was rather insensitive to attitude feedback gain. A value of 0.25, in conjunction with a velocity gain of 1.5, gave desirable response characteristics for the attitude command system and was used subsequently.

In figure 5 the fuel required to change pitch attitude 30° and stabilize in different time intervals is compared for the three systems. Yaw and roll results are not presented, but these results would be comparable. As might be expected, the slower maneuvers require less fuel than the faster maneuvers. It is apparent that the velocity and attitude command systems are about as economical as the acceleration command system. These curves are near minimum fuel required for these maneuvers and are much more easily realized with the velocity or attitude system than with the acceleration command system, as is illustrated in figure 6. It should be noted that the pilot control manipulation for the velocity and attitude systems is much less than for the acceleration system for satisfactory completion of the task. Initial attempts to change attitude with the acceleration system usually resulted in overcontrol and invariably resulted in more control manipulation.

The results discussed have concerned ideal systems with ideal rocket characteristics. In figure 7 is shown the effect of practical rocket thrust response on the relative fuel required for the stabilization task. Practical rocket response is characterized by a delay and buildup time. Thrust buildup times to 0.4 second were investigated and had no measurable effect on the performance of the systems. Delays up to 0.4 second, which should cover the range of practical delays, had little effect on the relative fuel for any of the three systems. For the large delay of 0.8 second the velocity and attitude systems showed only a small increase in relative fuel, but the acceleration system showed a large increase. These trends were even more evident during orientation tasks.

To gain some insight into the effect of dynamic pressure on the control task with reaction controls, stabilization tasks were performed at constant dynamic pressure. The results of these tests are shown in figure 8. It can be seen that with the velocity and attitude systems there was little effect of dynamic pressure. With the acceleration system, dynamic pressure can have a marked effect, depending on pilot technique and effort expended. With very close attention to the task, the efficiency of this system can approach that of the velocity or attitude command systems; however, many maneuvers, though not out of control, resulted in the fuel required that is indicated by the upper bounds of the crosshatched area. The dynamic pressure region of 5 to 10 pounds per square foot appears to be a very demanding region for precise control with the acceleration system because of dihedral effect.

Figure 9 extends these results by simulating the initial buildup in dynamic pressure during a typical entry without damper augmentation. Constant Mach number was assumed for this maneuver. Shown are time histories of dynamic pressure, sideslip, yaw control, bank angle, and roll control for the acceleration (solid line) and velocity (dashed line) command systems. It was the task of the pilot to recognize a sideslip misalinement, to zero sideslip, and to maintain control of the airplane during the dynamic pressure buildup. Successful entry could be accomplished with either of the control systems. As dynamic pressure increased, it became necessary to control the sideslip precisely to prevent large excursions in roll. The velocity command system minimized this task; whereas, with the acceleration system the task was more difficult. Roll excursions of considerable magnitude were evident especially in the higher dynamic pressure range. It should be noted, however, that in this dynamic pressure range the aerodynamic controls would be of increasing importance. With the attitude command system, entry was accomplished without pilot control.

CONCLUDING REMARKS

A simulator study of reaction controls has shown that:

A velocity or attitude command reaction control system would facilitate the task of orientation and stabilization in regions of low dynamic pressure.

All the systems were insensitive to lags that might be encountered in practical rocket systems, but at large lags the effectiveness of the proportional acceleration system deteriorates much more rapidly than does the effectiveness of the other control systems.

Dynamic pressure complicates the stabilization and orientation problem by aerodynamically coupling yaw and roll, but this complication only serves to emphasize the superiority of the velocity and attitude command systems over the acceleration system.

The attitude command system was superior to the velocity command system as a stabilizing device, but the velocity command system was preferred for orientation.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
Edwards, Calif., April 14, 1958.

TABLE I.- ASSUMED CHARACTERISTICS OF THE RESEARCH AIRPLANE

[M = 4.5]

Physical characteristics:	
Wing area, sq ft	200
Wing chord, ft	10.2
Wing span, ft	22.4
Airplane mass, slugs	420
Moments of inertia:	
About X-axis, slug-ft^2	3,500
About Y-axis, slug-ft^2	73,000
About Z-axis, slug-ft^2	75,000
Aerodynamic characteristics:	
Damping-in-roll derivative, C_{l_p}	-0.16
Rolling moment due to yawing velocity cross derivative, C_{l_r}	0.01
Effective dihedral derivative, C_{l_β}	-0.086
Damping-in-yaw derivative, C_{n_r}	-0.91
Yawing moment due to rolling velocity cross derivative, C_{n_p}	-0.1
Directional stability derivative, C_{n_β}	0.17
Pitch-damping derivative, $C_{m_q} + C_{m_{\dot{\alpha}}}$	-4.5
Longitudinal stability derivative, C_{m_α}	-0.30
Lift-curve slope, C_{L_α}	1.6
Lateral-force derivative, C_{Y_β}	-0.86

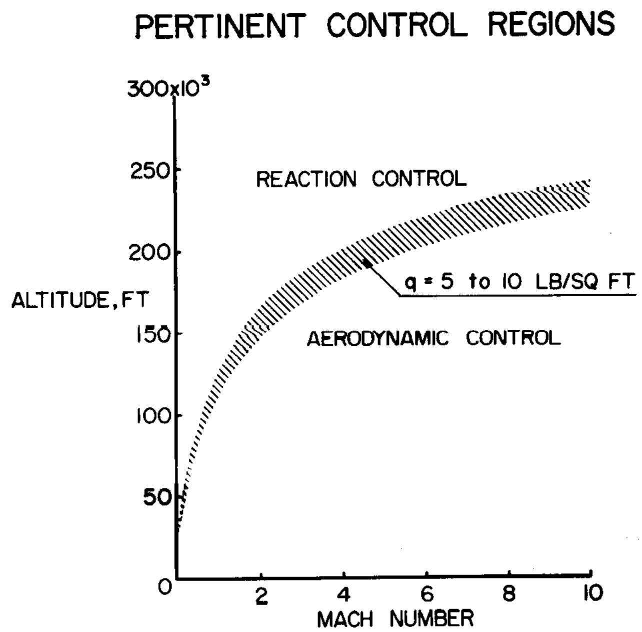
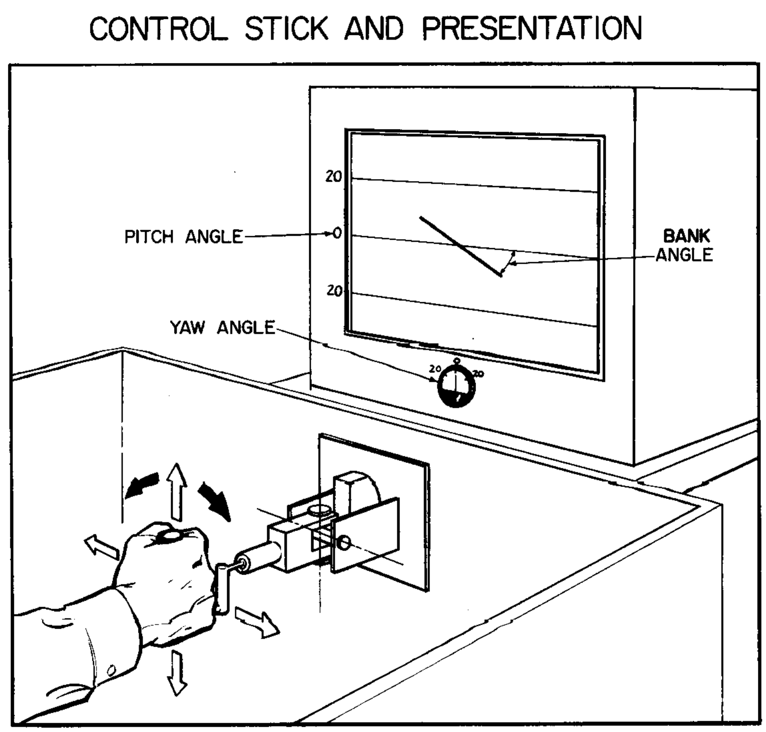

PERTINENT CONTROL REGIONS
300x10³
250
200
150
100
50
0
ALTITUDE, FT
REACTION CONTROL
q = 5 to 10 LB/SQ FT
AERODYNAMIC CONTROL
2
4
6
8
10
MACH NUMBER

Figure 1


CONTROL STICK AND PRESENTATION
20
PITCH ANGLE
0
20
BANK
ANGLE
YAW ANGLE
20
20

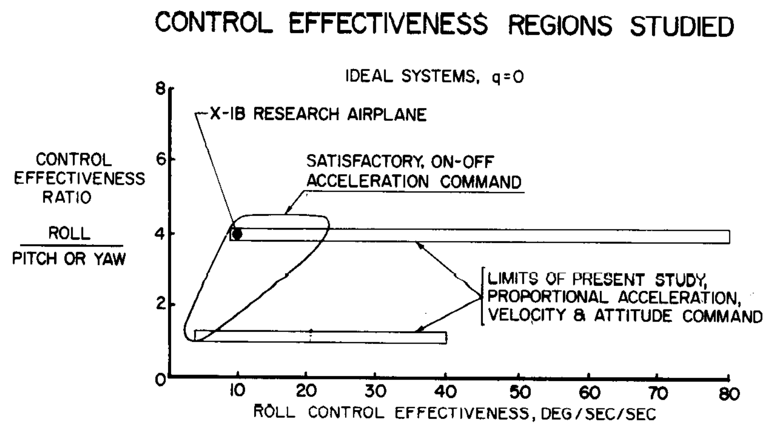


Figure 3

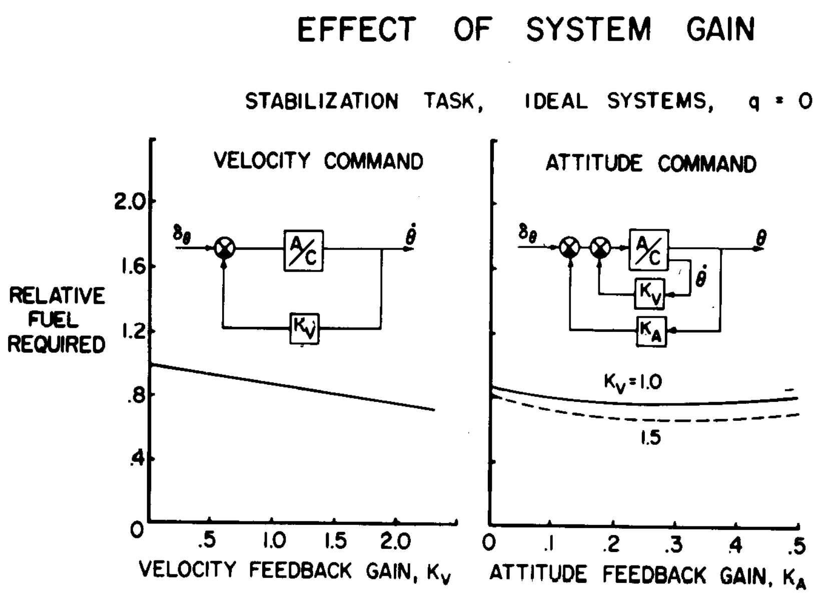


Figure 4

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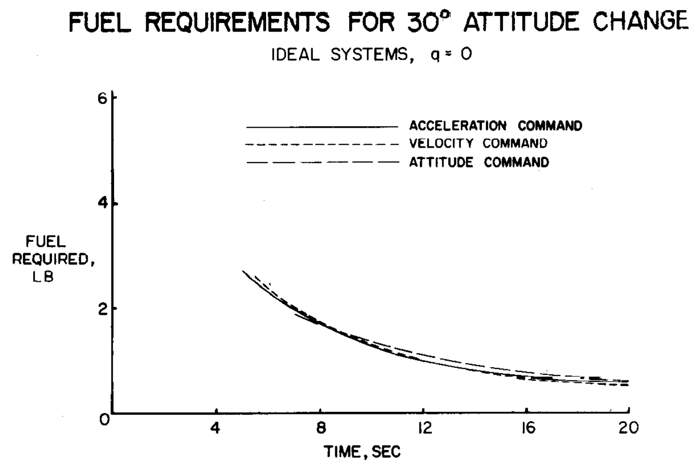

Figure 5

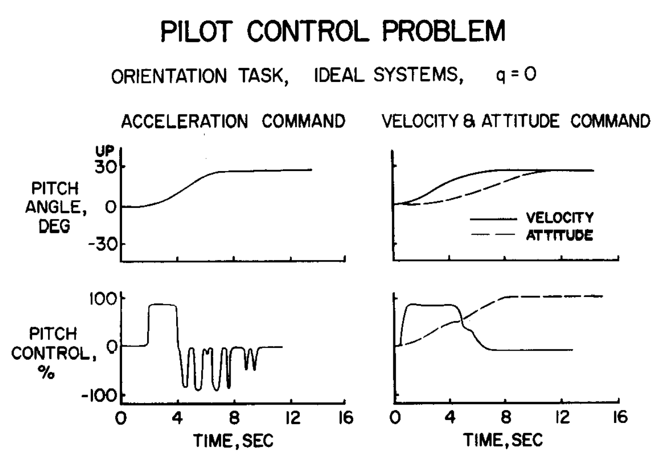

Figure 6

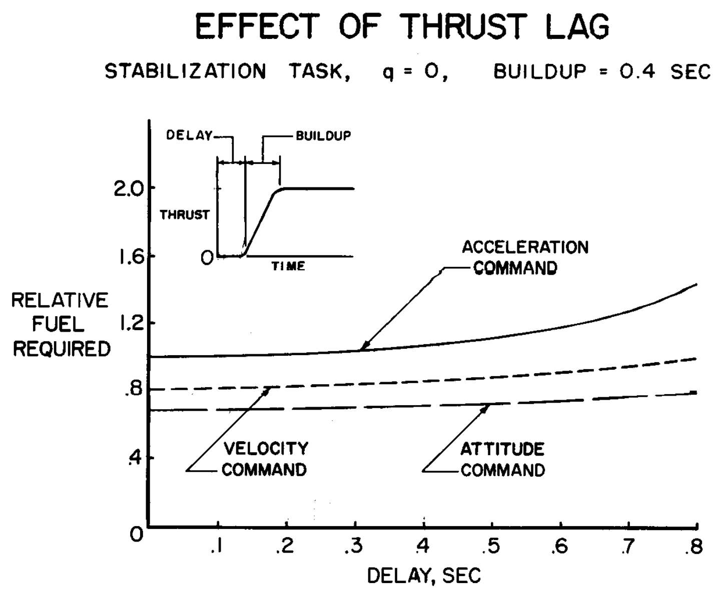

Figure 7

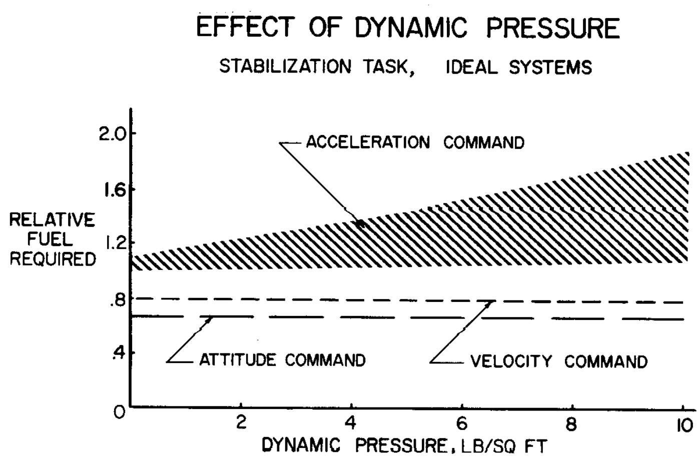

Figure 8

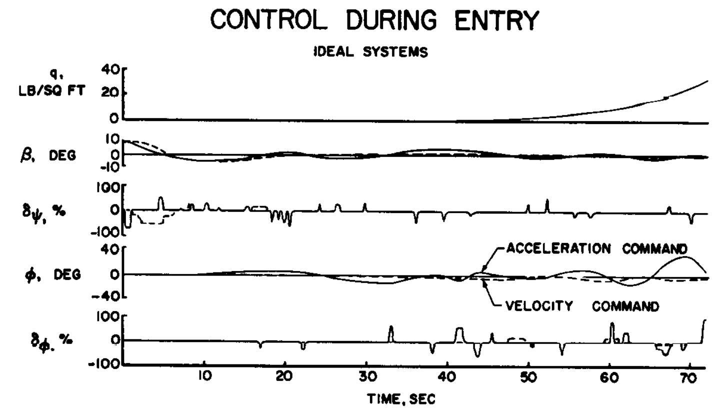

Figure 9

NACA - Langley Field, Va.